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# Optical coupling of flexible microstructured organic light sources for automotive applications

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**Abstract**

In this paper, we report on modelling and processing of customised optical patterns coupled with microstructured large area organic light emitting device (OLED) sources for automotive lighting. Different approaches for the optical control of the light emitted from an OLED are discussed and compared with the aim to fulfil automotive specifications for the following devices: side-marker, ceiling light and glove-box illuminators.



*Keywords:* OLEDs; Microstructuring; Thin films; Optical modelling

## 1. Introduction

The discovery of efficient electro-emission from organic molecules, processed as thin films [1] and polymers [2] organic light emitting devices (OLEDs), has attracted wide interest due to possible applications as displays, innovative devices for optoelectronics and novel light sources. Novel light sources based on OLEDs imply a considerable impact both in production processes and product innovation. OLEDs-based light sources possess major advantages with respect to bulb-lamps, discharge-tubes or LED sources. The main attractive aspects comes from the possibility offered by organic molecules to be easily deposited, with a variety of techniques, as multi-layers thin films on flexible optical substrates, opening the way to fabrication of geometrically adaptable, styling and design-sensitive high efficient light sources. Among the variety of possible applicative fields where OLED light sources can be exploited, we focussed our research effort on the Automotive sector. In particular, three different devices are investigated and developed. Two of them are for internal automotive application, namely ceiling light and glove-box illumination, and one for external automotive application, namely a side-marker. The ceiling-light device require a particular light distribution for fulfilment of given automotive specifications. It means that we must be able to control the emitted radiation. Moreover, we should note that in general in light emitting devices only a fraction of the generated light can escape the device. In standard OLEDs configuration, almost the 80% of the generated light is lost due to waveguiding and total internal reflection [3]. In order to improve the device out coming light, different methods have been explored: introduction of rough or textured surfaces [4,5], reflecting surfaces and distributed Bragg reflectors [6,7], and interesting two-dimensional photonic structures [8,9]. Another interesting method to enhance light out coupling efficiency by using an ordered array of micro-lenses has been demonstrated recently [10,11]. In our case, the optimisation of the out coming light electro generated in OLEDs is only a part of the problem since we aim to control the light distribution and divergence. Our envisioned approach enabling control of light distribution from an OLED light source include modelling and patterning of the light source, design and fabrication of suitable micro-optics coupled to the flexible transparent organic light emitting diode substrate.

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## 2. Results and discussion

The OLED light source considered in this work is a vacuum sublimed standard two-layer thin film of TPD (*N*,*N*′-diphenyl-*N*,*N*′-bis(3-methyl-phenyl)-(1,1′-biphenyl)-4,4′-diamine) and $Alq_3$ (tris-8-hydroxyquinoline), grown onto a patterned ITO plastic foil provided with a barrier multi-layer (Barix coating) to protect the device from oxygen and moisture [12]. Thickness of the deposited organic layers has been measured both with scanning probe and micro-stylus profiler techniques allowing a high reproducible thickness control via quartz balance measurement during vacuum growth. The thin film growth vacuum conditions were the ones of a standard high vacuum equipment with a base pressure of $5 \times 10^{-8}$ mbar. Thin films of TPD (50 nm) and of $Alq_3$ (60 nm) have been deposited onto a patterned ITO surface acting as the anode of the final device. Aluminium, acting as the cathode, has been evaporated through a metal mask in order to form a matrix of pixels of electroluminescent sources 50 $\mu m^2$ each covering a surface of 2 $cm^2$. The obtained device is shown in Fig. 1.

In order to exploit flexible OLEDs as automotive light sources the problem of efficient light emission optical control has to be addressed and solved. Depending on the light-source properties, different optical solutions can be adapted and interfaced or integrated to the light source. In Table 1, we summarise the fundamental characteristics and basic requirements for different optics. First of all, we should note that electroluminescence OLED emission is, in general, in-coherent and follows a Lambertian distribution. This optical property of the source rule out, at least at the first order, the possible use of phase hologram and diffractive lenses as optical imaging elements (see Table 1). For the remaining two optical solutions, refractive and Fresnel lenses, an OLED pixel model is necessary in order to allow the micro-optics design. Such a model was obtained starting from the following hypothesis: (1) point source emission at 20 nm inside the $Alq_3$ layer starting from the $Alq_3$ and TPD interface [13]; (2) geometrical ray propagation; (3) randomly polarised light; (4) Fresnel laws at interfaces. Previous work on optical modelling of OLED considering the effective emission zone as an important parameter for out coupling is taken into account [14]. To correctly model our OLED source it is important to know the $n(\lambda)$ dispersion curve of the organic layers used in the device to simulate. Literature values were used to optically simulate the Alq3 layer and a measurement approach was applied to obtain the dispersion curve of the TPD layer.

Starting from the hypothesis that TPD is not absorbing in the wavelength range between 460 and 680 nm [15], it is possible to consider the TPD refractive index as purely real in that wavelength range, we then calculate this parameter considering the measure of the transmission curve $T(\lambda)$ of a TPD organic thin film of known thickness $d$ and using the following formula to fit the data:

$$T(\lambda) = \frac{4 n_{\mathrm{air}} n_{\mathrm{glass}} n_{\mathrm{TPD}}^2}{n_{\mathrm{TPD}}^2 (n_{\mathrm{air}} + n_{\mathrm{glass}})^2 \cos^2(2\pi n_{\mathrm{TPD}} d/\lambda) + (n_{\mathrm{air}} n_{\mathrm{glass}} + n_{\mathrm{TPD}}^2)^2 \sin^2(2\pi n_{\mathrm{TPD}} d/\lambda)}$$

Here, we used a Taylor series expansion for the unknown refractive index $n_{\mathrm{TPD}}$ of the form $n(\lambda) = n(\lambda_0) + n'(\lambda_0)(\lambda - \lambda_{\bar{0}}) + 0.5 n''(\lambda_0)(\lambda - \lambda_0)^2$ with $\lambda_0 = 500$ nm.

The experimental dispersion curves $n(\lambda)$ calculated for three TPD samples of different thickness lie within an error of $\pm 0.02$ (see Fig. 2).

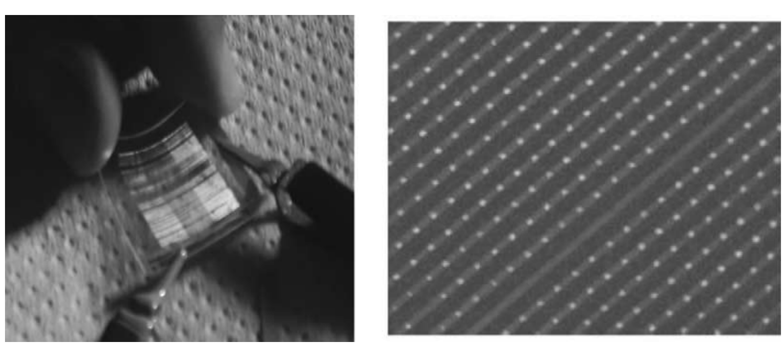

Fig. 1. OLED sample on flexible substrate (PET) with stripes 50 μm wide (left) and a microscope image (magnification 100×) of OLED pixels 50 μm × 50 μm large on flexible substrate (right).

Table 1
Fundamental characteristics and basic requirements for different optics

| Element type | Sag. (μm) | λ-dependence | Special |
|---|---|---|---|
| Refractive lenses | 20–40 | Low | Large sag., type spherical |
| Refractive Fresnel lenses | 10–20 | Low | Reduced sag., limited number of zones |
| Diffractive lenses | <15 | High | Spatial coherence, number of zones, stray-light |
| Phase hologram | <10 | Medium–high | Requires high spatial coherence |

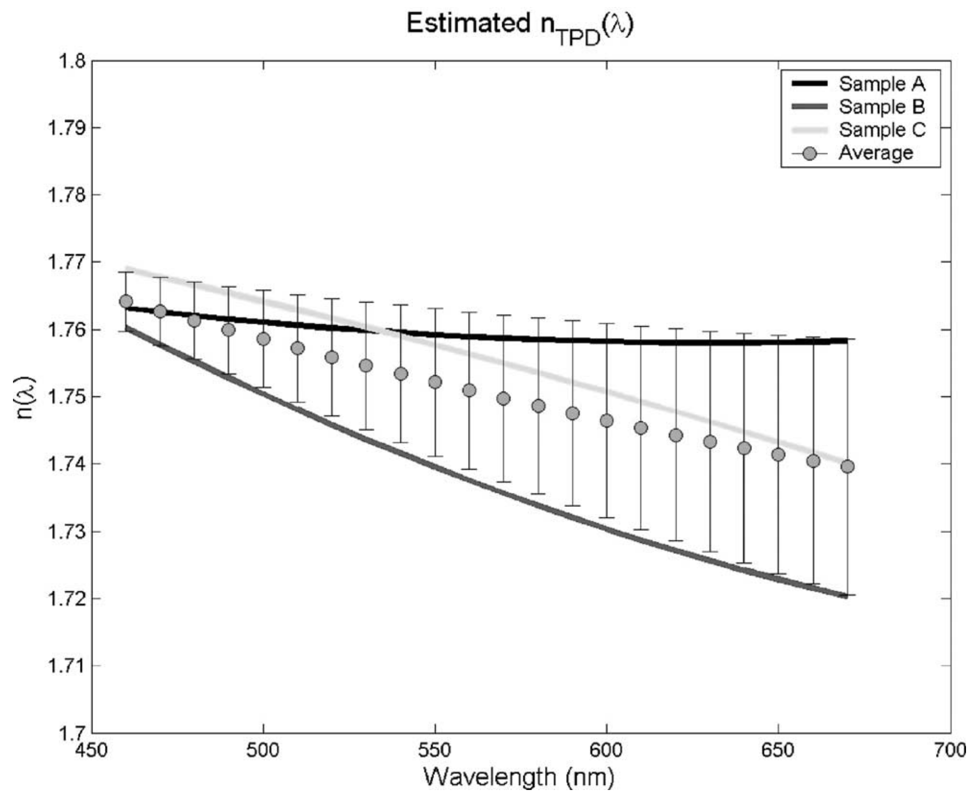


Fig. 2. Dispersion curve of the TPD real part of the refractive index calculated in a wavelength range from 460 to 680 nm. A fitting procedure was used to obtain this curve from a measure of wavelength dependent film transmission at three different known TPD film thickness.

We then simulate our source using these parameters in a ray-tracing program. In particular, we evaluate the different pixel step distance and the substrate width to avoid an heavy overlap of the rays emitted from neighbouring pixel sources. The results of these simulations suggest a pixel step and a substrate thickness both in the range of 100 $\mu$m.

To distribute the emitted light in the optical field required by the an automotive application (ceiling light) refractive micro plano-convex lenses were calculated with a maximum sag. of some tens of microns.

For the micro-lenses fabrication we have explored the following approaches: (1) hot embossing directly onto the flexible substrate; (2) hot embossing + assembly to the patterned substrate; (3) UV-casting.

The first approach give rise to serious problems since the barrier layer and the ITO electrode are damaged during the process. In Fig. 3, we show the results of UV-casting of reflow lenses and alignment to patterned flexible ITO substrate. The preliminary results are encouraging our approach to exploitation of OLEDs as innovative light sources for automotive applications.

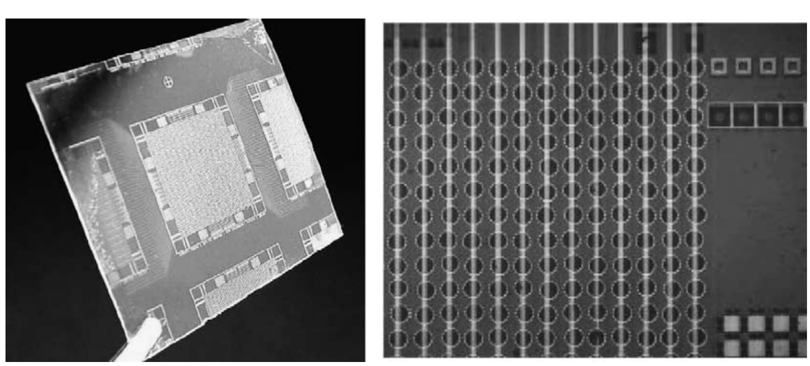

Fig. 3. Image of UV cast reflow lenses integrated on a plastic substrate with ITO etched 50 $\mu$m stripes, general view (left) and microscope image (magnification 100×) of the micro-optics and ITO stripes matching (right).

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